

# Optical-fiber-to-waveguide coupling using carbon-dioxide-laser-induced long-period fiber gratings

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Optical fibers are expected to play a role in chip-level and board-level optical interconnects because of limitations on the bandwidth and level of integration of electrical interconnects. Therefore, methods are needed to couple optical fibers directly to waveguides on chips and on boards. We demonstrate optical-fiber-to-waveguide coupling using carbon-dioxide laser-induced long-period fiber gratings (LPFGs). Such gratings can be written in standard fiber and offer wavelength multiplexing–demultiplexing performance. The coupler fabrication process and the characterization apparatus are presented. The operation and the wavelength response of a LPFG-based optical-fiber-to-waveguide directional coupler are demonstrated. © 2005 Optical Society of America

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Optical interconnects show significant promise for enabling high-speed input–output in future gigascale-integrated microelectronics systems. Applications of optical interconnects currently being developed include optical clock distribution, data input–output, and high-speed communication between systems.<sup>1–3</sup> Optical fibers are expected to play a role in chip-level and board-level optical interconnects.<sup>4</sup> Therefore, efficient coupling of light from optical fibers to chip- and board-level waveguides will be necessary.

A number of different configurations for accomplishing the required fiber-to-waveguide coupling have been investigated. High efficiency was achieved for fiber endface-to-waveguide coupling using D-shaped optical fiber positioned in accurately fabricated alignments.<sup>5</sup> Compact nanotapers, functioning as mode converters, have been used to couple light from optical fibers to silicon waveguides and photonic crystals.<sup>6</sup> Diffractive optical elements (DOEs) can also be used to couple light emerging from fibers into waveguides.<sup>7</sup> While relatively high coupling efficiencies have been reported for nanotaper- and DOE-based couplers, most of the configurations mentioned still require precise alignment of the fiber endface and the coupler device if one is to avoid large insertion losses. Most configurations also require additional or special fabrication steps to create the integrated coupling devices. It follows that there are several advantages to using a coupling device that is intrinsic to an optical fiber and does not require access to fiber or waveguide endfaces. Such a coupler would be especially well suited for facilitating direct optical fiber interconnects and for optical interconnect prototyping.

Fiber gratings are one type of intrinsic device that can be used for coupling light into and out of optical structures. It has been proposed that slanted fiber gratings be used to perform coupling.<sup>8</sup> In addition, long-period fiber gratings (LPFGs) can also be used. Typical LPFGs couple light from core-guided modes to cladding-guided modes near specific resonant

wavelengths. The cladding mode coupling function of LPFGs can be used to couple light into other fibers or waveguides. One potential type of LPFG-based fiber-to-waveguide coupler is shown in Fig. 1; this type of coupler is compatible with both multimode and single-mode waveguides (with suitable alignment). With multiple LPFGs existing in a given optical fiber segment, light can be coupled between multiple waveguides on separate boards and (or) chips.

One particular category of LPFGs, carbon-dioxide-laser-induced ( $\text{CO}_2$ -laser-induced) LPFGs, offer several advantages for performing coupling. These gratings can be written into standard telecommunications optical fiber, they are inexpensive to fabricate, and their coupling properties can be readily altered. In addition, the asymmetric refractive-index profile induced by one-sided exposure to  $\text{CO}_2$ -laser-light<sup>9</sup> can be used to enhance the coupling.

With the potential advantages described above, a LPFG-based fiber-to-waveguide coupler would be a useful device for optical interconnect systems. LPFG-based couplers have been demonstrated previously, but primarily for achieving coupling between two

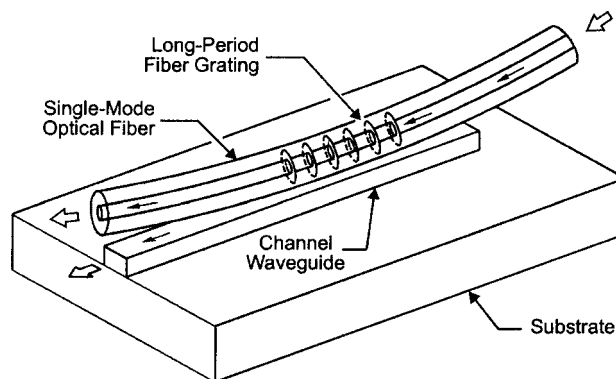


Fig. 1. Diagram of a LPFG-based optical-fiber-to-waveguide coupler. Light traveling in the core of the fiber is coupled into a cladding-guided mode by the LPFG. A portion of the light in the cladding mode is then coupled into the waveguide.

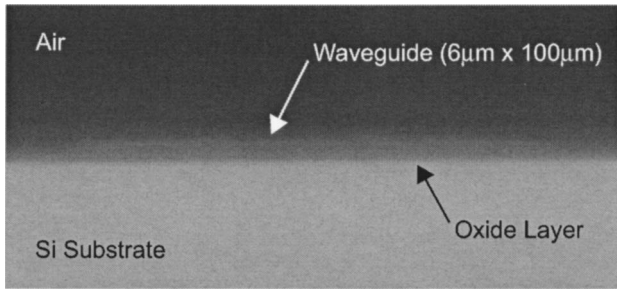


Fig. 2. Reflected-light image of the waveguide endface. The substrate containing the waveguides is cleaved to produce a smooth endface to facilitate observation of light emerging from the waveguide.

parallel fibers, for coupling between two fiber endfaces, or for coupling between a laser diode and a fiber (using a microlens).<sup>10–12</sup> In this Letter we present what is believed to be the first experimental demonstration of optical-fiber-to-waveguide coupling using a CO<sub>2</sub>-laser-induced LPFG. A wide variety of formats for a LPFG-based coupler are possible, but the particular version presented in this Letter has the configuration shown in Fig. 1 and acts as a directional coupler. After briefly describing the coupler operation, fabrication, and characterization apparatus, the role of the LPFG in performing coupling is demonstrated and the wavelength dependence of the coupling is illustrated.

The LPFG used to perform coupling was fabricated in Corning SMF-28 single-mode optical fiber by periodic exposure of the fiber to CO<sub>2</sub> laser light<sup>13</sup> to exhibit coupling to a cladding mode in the 1550 nm telecommunications wavelength band. The grating has a period  $\Lambda$  of 640  $\mu\text{m}$  with 37 total periods. The combination of period spacing and number of periods yields a LPFG approximately 23.7 mm long. The optical fiber containing the LPFG is prepared for use by removing any buffer material on the fiber within 38 mm from the start of the grating. The fiber is then cleaved at the end of the uncoated section away from the grating (to facilitate positioning on the waveguide).

The waveguide into which light is coupled from the optical fiber is fabricated from Avatrel 2190P photopolymer (from Promerus) on top of a 2  $\mu\text{m}$  oxide layer grown on a silicon substrate.<sup>14</sup> Air serves as the cladding layer of the waveguide (away from the optical fiber–waveguide interface), while the oxide layer acts as the substrate layer. The channel waveguide is 6  $\mu\text{m}$  high by 100  $\mu\text{m}$  wide, as shown in Fig. 2, with an overall length of 38 mm. At a wavelength of 1550 nm, the refractive index of the polymer is approximately 1.50, while that of the oxide layer is approximately 1.46. For the wavelength, waveguide dimensions, and refractive-index values given, the waveguide supports the first two to three modes in the vertical (6  $\mu\text{m}$  height) direction and is multimodal in the horizontal direction.

To observe coupling of light from the optical fiber to the waveguide, the coupler is assembled on an optical fiber endface characterization apparatus. The waveguide is secured on top of a three-axis linear stage,

and the waveguide endface is positioned at the focal plane of an endface inspection microscope (with a 20 $\times$  objective). The optical fiber containing the LPFG is inserted into a fiber positioner and then aligned over the waveguide with the aid of a long-working-distance microscope positioned over the substrate. A small amount of index-matching gel (with a refractive index of approximately 1.46) is applied to the bottom surface of the optical fiber over the entire 38 mm length (to enhance coupling) before the fiber is lowered into contact with the waveguide. The optical fiber containing the LPFG and the waveguide are in contact (parallel) over most of the waveguide length, with the grating close to the start of the waveguide and the optical fiber ending 3 mm before the waveguide endface.

With the coupler assembled on the characterization apparatus, a tunable laser source is coupled to the optical fiber end away from the waveguide. Use of the tunable laser source enables the wavelength response of the coupler to be measured. The incident light was randomly polarized. Light emerging from the waveguide endface is observed by use of the endface inspection microscope in conjunction with a vidicon near-infrared camera.

To demonstrate the effect of the CO<sub>2</sub>-laser-induced LPFG, the light emerging from the waveguide endface was observed for an optical fiber without a LPFG and for a fiber containing the LPFG. The resulting images of the waveguide region are shown in Fig. 3. No light is coupled into the waveguide for the optical fiber without a LPFG, whereas light is clearly observed emerging from the waveguide endface for the fiber containing the CO<sub>2</sub>-laser-induced LPFG, thus indicating that coupling occurs. The images are normalized to the peak observed gray-scale level after subtracting background light levels. Light observed in the LPFG case is also clearly confined to the 6  $\mu\text{m}$  high by 100  $\mu\text{m}$  wide waveguide region. As anticipated from slab waveguide theory, the light in the waveguide is highly multimodal in the horizontal direction but approaches single-mode operation in the vertical direction. The coupling efficiency is esti-

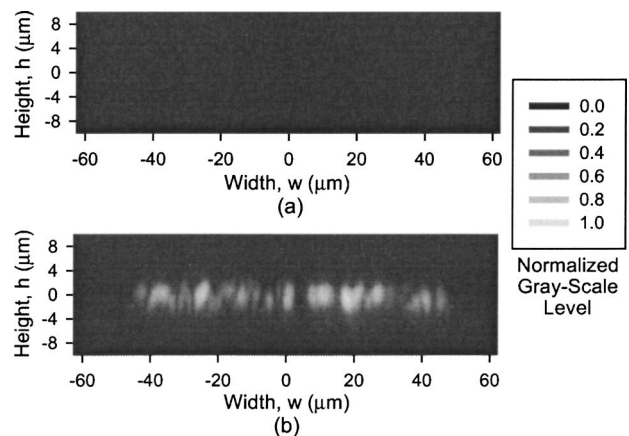


Fig. 3. Light observed emerging from the waveguide endface for an optical fiber positioned on top of the waveguide (a) without a LPFG and (b) with a CO<sub>2</sub>-laser-induced LPFG. The laser source wavelength is 1540 nm.

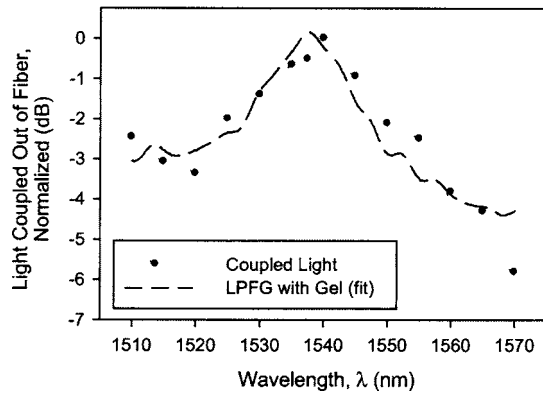


Fig. 4. Normalized summation of image gray-scale values over the waveguide region of light coupled into the channel waveguide for each test wavelength (filled circles) and the fitted coupling spectrum for a LPFG surrounded by index-matching gel (dashed curve). The close agreement between the two indicates that the wavelength response of the coupler follows from the wavelength characteristics of the LPFG.

rated to be 1–5% for this nonoptimized test configuration.

The wavelength response of the LPFG-based optical-fiber-to-waveguide coupler was measured by varying the source wavelength and observing the corresponding changes in the light emerging from the waveguide endface. The normalized summation of image gray-scale values over the waveguide region for 14 test wavelengths is plotted in Fig. 4. The light coupled into the waveguide from the LPFG decreases as the source wavelength shifts away from the grating resonant wavelength. The wavelength response of the coupler mimics the wavelength resonance characteristics of the LPFG when the grating is surrounded by matching gel. The relationship between the wavelength dependence of the coupling and the LPFG wavelength spectrum is verified by the close agreement between the (fitted) cladding mode coupling spectrum of a LPFG surrounded by matching gel and the coupler wavelength response data, as shown in Fig. 4. The cladding mode coupling spectrum in Fig. 4 is fitted in magnitude, using a least-squares approach, to the coupler response data by adjusting the amplitude and bias. Also evident from the wavelength response measured for the coupler is the increase in light levels at shorter wavelengths (near 1510 nm). This increase is due to another cladding mode resonance that is present at a shorter wavelength.

In conclusion, we have demonstrated optical-fiber-to-waveguide coupling using a CO<sub>2</sub>-laser-induced LPFG and have measured the wavelength dependence of the coupler. The demonstrated device does not require access to fiber or waveguide endfaces to

perform coupling, and the observed wavelength-dependent coupling would be valuable for interconnect systems employing coarse wavelength-division multiplexing. In addition, the CO<sub>2</sub>-laser-induced LPFG used to achieve coupling can be written in standard telecommunications optical fiber. The particular LPFG-based coupler demonstrated here performs as a directional coupler and has the highest coupling efficiency when the refractive index of the waveguide is close to that of the fiber cladding; the coupling efficiency drops significantly as the difference between the cladding and waveguide indices increases. Other implementations (such as incorporating a CO<sub>2</sub>-laser-induced LPFG into a D-shaped optical fiber) may have additional favorable characteristics.

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